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by

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1. Introduction

Very few economists, I imagine, would dissent from a claim that technology and its correlates occupy a central role in the performance of real economies and that changes in technology are central to an understanding of growth and development, to the theory of competition and the nature of the firm, and to the explanation of shifts in comparative advantage, as well as and many other problems. As the bridge between the productive factors and human satisfaction it is an integral part of any theory of coordination and of the structure of economic life. Ever since the pioneering work of Abramovitz and Solow in the 1950s economists have been acutely aware of the fact that increases in the productivity of a representative bundle of inputs account for the bulk of aggregate economic growth[1]. But this idea was broadly accepted by earlier economists among whom Smith, Marx, Marshall and Schumpeter would certainly be in the forefront. The idea that these changes in productive

[1] See Abramovitz (1956, 1989, chapter 1), and Solow,(1957). We might note that if the neoclassical growth steady growth story is taken seriously then steady growth implies that all of the growth of output per employee is attributable to technical progress because the associated rate of capital deepening is induced by, and could not occur independently of the rate of technical progress. In familiar terminology, the shifts around the production function are induced by shifts in the production function. Outside of the neoclassical framework this point was developed in detail in Rymes (1971). For further critical assessment see Nelson (1973)

efficiency are closely tied to changes in underlying technology is widely accepted even if only by assertion for technology is always a shadow cast by the activities in which we are interested. It is not redundant, therefore to poise the question “what do economists mean by technology?”

Unfortunately, there is no straightforward response to this question, and any particular answer usually depends on the wider framework of problems in which a concept of technology has to fit. The concept of technology that is central to an evolutionary account of uneven economic development, for example, is far removed from the concept that is required in a theory of a static or stationary economic equilibrium. What they all have in common is the idea that whatever technology is it is inseparable from the exercise of human agency and must therefore have features that are compatible with the limitations of human agency. By technology, we can mean a body of understanding of cause and effect in human minds, as with the codified realisations of productive knowledge in operating manuals, blueprints, recipes, scientific papers and so on; as the capacities and skills that permit action whether individually or in cooperation with others, not all of which will be written down; and, the purposefully organised and designed built structures within which action tales place- the realised, human built world as Hughes (2004) has called it.

Technology is a complex notion and to develop this theme we shall proceed in three stages, beginning with the idea of a production function and the more primitive notion of a productive activity, then discussing the differences between a production menu and the material and energy basis for production, and, finally, introducing some brief observations on the main trajectories of technical change that follow from the energy and materials perspective. Throughout there is a general theme that technology is also a matter of the organisation and management of production systems, as well as of direct productive knowledge in a mechanical or chemical sense. Its systems are composed of interrelated activities that have an architecture comprising structures of modules and components[2]. It is this perspective that places our discussion firmly within a division of labour tradition, albeit with modern twists.

[2] As far as I know the fruitful idea of a technology architectures was formulated by Henderson and Clark, (1990) The theme has been richly developed by Langlois and Robertson (1995) in their discussion of the boundaries of the firm

2. Technology and the Production Function

There is little to be said here that has not been said many times before, but some brief observations will help to put our discussion into perspective. In Adam Smith the nature of technology is subsumed within the idea of the division of labour between and within different lines of production. The principle idea is of the sequencing of production activities in a number of complementary tasks or stages in production. . It is the idea of sequencing that connects with the capital saving nature of specialisation (fewer sets of productive instruments are needed) and with the Babbage principle that the size of the production team that maximises the productivity of labour is that size which satisfies the principle of common multiples (Leijonhvud,1986). Smith's attitude to technology is closely related to the dynamics of his theory of economic development, in which technical change amounts to an ever more refined division of labour and is induced by and in turn induces the growth of the market. This is the view that was subsequently taken up in Allyn Young's famous paper and which was discussed extensively by Marshall[3]. In particular, the division of labour is a dynamic principle stimulating the invention of new machinery and new knowledge in general. While the accumulation of skill in any fine task is likely to be bounded, the prospect of inventing sequences of better machines is not. As Frank Knight once expressed it, the fundamental point about the division of labour is that it is also system for increasing the efficiency of learning and thus the growth of knowledge (Knight, 1933, p. 18).

Despite its importance to any discussion of how economic means are made operational, modern economics, almost universally, has very little to say about the division o f labour. Instead, the primitive notion of technology runs in terms of a specification of the quantities of various inputs required to produce a given quantum of a particular kind of output over some definite time interval, and given the understanding of the state of the art in the minds of those operating the process. This perspective of technology as a menu (for it is less than a blueprint) appears most obviously in the theory of production and consequently in the theory of the firm, which is taken to be the controlling and managing unit of any production activity. All that is needed to specify the technology are the lists of inputs and outputs, all other dimensions are of no economic interest. Technology is simply the unexplained constraint on

[3] Young (1928) and Marshall (1920) Marshall devotes the great part of book 4 to the many ways in which the division of labour develops over time within the framing idea that knowledge and organisation are the two most powerful of productive forces. Kaldor (1972) is very much in this tradition.

human action in relation to production. It is not even considered necessary to specify the inputs in any detail, nor to account for what it is they do in production. The menu approach has a long tradition. No less an authority than Lionel Robbins opined that "The technical arts of production are simply to be grouped among the *given* factors influencing the relative scarcity of different economic goods" (1932, p. 33)[4]. In neoclassical economic theory, more generally, the formulation of technology has a long history, going back at least to Wicksteed, who, in his 'The Co-ordination of the Laws of Distribution" (1894), states his central premise as follows: "The Product being a function of the factors of production we have *P=f(a .b. c,……)*". This abstract way of representing the recipe for a production process has not changed in its essentials since then. Half a century later, Samuelson (1947) makes virtually the same statement, namely, "We assume as given by technical considerations the maximum amount of output *x*, which can be produced from any given set of inputs $(v_1,\ldots,v_n)$ …." (p. 57). It is repeated without limit or significant variation in countless economic texts (eg., Bronfenbrenner, 1971; Ferguson, 1971). Murray Brown (1966) summed up the general position very clearly in terms of four abstract properties of any technology menu, namely, the efficiency with which inputs generate outputs, the degrees of economies of scale, the relative proportions in which the inputs are employed, and the ease of substituting one input for another.

The production function is a derived notion; it is based on the more fundamental concept of a productive activity, a particular way of getting certain things done[5]. A menu, however, only specify the quantities of all the inputs that are required to produce a given quantum of output within a given period of time, not the how of getting things done. It presupposes a particular state of understanding but the specification of the requisite blueprint or recipe, how the inputs are combined, the sequences that are possible, the spatial separation of the stages of an activity, the rationale for why things are done in a particular way are not part of the activity concept. The set of activity menus in relation to a particular line of production defines the productive opportunity and of all the possible menus that are known, a subset defines the efficient frontier, depicting those activities that generate the greatest quantum of output from

[4] Commenting further on this in relation to the practice of economic history he adds, "The precise shape of the early steam engine and the physical principles upon which it rested are of no concern of the economic historian as economic historian. For him it is significant because it affected the supply of and the demand for certain products and certain factors of production, because it affected the price and income structures of the communities where it was adopted", p. 41.

[5] Koopmans, (1951)and Dorfman, Samuelson, and Solow (1958)

a particular quantum of inputs, and, with sufficient continuity in the set of activities, the efficient frontier becomes the traditional, smooth production function[6].. Furthermore, the inputs are distinguished one from another only by their imperfect substitutability, the basis for the law of diminishing marginal returns, not for their intrinsic characteristics. Implicit here is the idea that the technical details of production are an economic irrelevance, in that two quite different menus, drawing on different states of the art, are from the point of view of production economics the same method of production if they have the same transformative characteristics. A further important distinction is between the production function as a planning concept and the production function as a realised method of production (Schumpeter, 1954, p. 1027). In the first, ex ante context, what is currently known to the managers and their advising engineers and designers is the planning constraint on the selection of the most cost effective method available. It is what Salter (1960) called the best practice frontier, defined by the menu sets that are based on the most productive knowledge available. Once a design is chosen and embodied in a particular plant as an operational method, the scope ex post, for varying the production method may be severely circumscribed by the side constraints implicit in the embodiment of methods in capital structures. Hence the famous distinction made by Marshall between short run variations in the labour and material inputs that change the degree of utilisation of an existing plant, and longer run variations where the design of the plant may be altered and re-engineered in part or in whole to accommodate to changes in best practice knowledge. Of course, these distinctions are matters of degree and constitute a continuum of possible variations in production method rather than sharply delineated stages.

If we probe a little deeper into the menu then the question of the nature of the inputs needs to be addressed, in particular, the distinction between produced inputs and factor inputs. By factor inputs, the neoclassical economist means the services of the ultimate agents of production, land, labour and capital specified to different degrees of exactness. This in turn reflects a perspective on the production process as a linear transformation of the factor service inputs into final goods with the production of intermediate forms of goods as inputs implicitly netted out. This is quite different from the classical view of production in which

[6] Continuity yields well defined marginal products, and economically relevant region of the efficient frontier is only a subset of the technically efficient sub set, namely the region of operation for which, as input proportions vary, the marginal products of all the inputs are positive. The efficient economic domain was distinguished forcefully by Frank Knight (1921). A thorough, modern treatment of the limited region of economic efficiency is given in Ferguson (1971).

the role of intermediate produced means of production, from circulating materials in process to more durable capital instruments, is at the core of the treatment of production. Instead of focusing on the isolated menu for producing a particular good or service, the emphasis shifts to the system of production as a whole and the conditions for its reproduction and expansion. This gives rise to a circular flow perspective, in which goods are worked on to produce goods within an input output structure that captures a sophisticated division of labour in the production process (Kurz and Salvadori, 1995; Carter, 1970). If the system is to continue in a self sustaining way, the material inputs used up in one production cycle, including worn out capital goods, must be replaced from the outputs of that production cycle, giving rise to the distinction between gross output and net output from which later consumption and investment are drawn. In systems theory terms, this is a matter of the conditions for autopoiesis or self sustaining organisation. We note here that the price system now appears to have an extended logic, not only to generate income for the ultimate factors of production but also to generate the revenue required to purchase the produced materials and energy to reproduce the pattern of production. A related but different take on the same theme is provided by the Austrian stages of production concept in which the emphasis shifts to the sequential time phased nature of production goods produced at one date becoming available for further processing at later dates, until we reach the stage at which they become final goods (Menger, 1871, Hicks, 1973). Because the circular and the time phased views are different ways of dealing with the same phenomenon of goods in process, it is not surprising that they can be rendered as equivalent ways of representing a system of production in which time and structure are complementary concepts[7]. What all of these approaches have in common is the notion of a technology menu as the given and unexplained basis for productive activity

For many problems in static and stationary analysis, the activity as menu idea is perfectly sensible, all explanations take some elements as primitive and beyond the explanatory scope of the theory. The factor proportions theory of comparative advantage is an obvious example, where an assumed international identity of a given industry's technology across countries is a key element in the account of how trade patterns are generated. It is when we turn to problems of growth and development, and thus to questions of innovation and technological change, that the menu approach to technology becomes problematic, precisely

[7] See Burmeister, 1974 for a detailed elaboration of this point. The Sraffian analysis in terms of production in terms of dated quantities of labour falls into the same general category of time phased analysis. See Kurz and Salvadori, (1995), for extended discussion.

because growth and development are so closely connected to changes in technology. The central problem to be addressed is that the idea of crisply delineated menu choice sets begins to crumble between our fingers when we realize that enterprise, invention, localised, differentiating, creative process, and that the very conduct of economic activity gives rise to new technological knowledge and so induces corresponding changes in more basic understanding of the phenomena at work. One has to move beyond the idea of technology as the menu of inputs and outputs to a more finely detailed understanding of the multiple dimensions that characterise different ways of doing things. This is the basis for the idea that a blue print or recipe lies behind a particular menu, specifying what it means to get things done. But just as there is more to the blueprint than a menu so there is more to the actual doing than is specified in a recipe. What has to be added is knowledge of who is using the recipe because their personal knowledge and skills make a difference to what the recipe leads to. When a recipe is being articulated by an organisation (a firm, or university or medical centre, or public bureaucracy) this makes the specification of the origins of the menus in operation a particularly rich source of technological differentiation[8]. Instead of a crisp boundary between what is possible, what is impossible and what is technically irrelevant we have a region of technological possibilities in which a range of different menus and recipes co exist for carrying out the same activity

Rather than technological knowing it is technological ignorance that now comes to the fore, within an evolutionary, developmental perspective in which production possibilities are constrained by a lack of problem solving ability in relation to ends that are considered desirable. It is a scarcity of technological capability that induces the endless search for improvements in understanding of the productive arts; and, because scarcity is indeed a fundamental economic problem, it is hardly surprising that it continuously invites attempts to invent it away. Such a claim naturally suggests the idea that technology is itself the product of a production process that it is responsive to investment in knowledge creating activity which, in turn, is constrained by an set of menus and recipes for generating technological knowledge[9]. But this simply pushes the fundamental problems into the background,

[8] The blueprint idea is used in Robinson (1956) and developed in Salter (1960). The idea of technology as a recipe in practice is widely used in the evolutionary school of economists. See Winter (1967), Nelson and Winter (1982) and Dosi and Marengo(1994) for an introduction to the general perspective. On the localised aspects of technical change see Antonelli, (2001)

[9] This, of course, simply pushes the argument one stage back since no explanation is provided for the technology to produce technology. For one of the best accounts of induced innovation, one that recognises the importance of the relative ease of advancing knowledge in different directions see Binswanger (1974)

requiring an explanation of the technology to produce technology *ad infinitum*. Moreover, technology is not like any other output that can be measured in its own units. It is manifestly not a homogeneous stock in the sense that its magnitude can be reduced to a scalar measure, for there is no weighting system available by which we can reduce the knowing of different things to a common denominator (Metcalfe, 2002; Steedman, 2003). At best what is known is a heterogeneous set of incommensurable elements. The sense of heterogeneity is further deepened when we recognise that the recipes that underpin any input-output menu are also products of organisational and managerial knowledge, as well as technological and scientific knowledge in the narrow senses of human skill and of the laws of nature as applied to human artefacts. But these different kinds of knowledge are generated by different processes in different contexts, in response to different incentive structures and take place at different rates over time, and this combined with the incompleteness of any recipe set points to the ill-defined nature of production technologies. How specific activities are articulated will depend on the minds making and actuating particular decisions as to which recipe is to be used, and there is no warrant for the idea that firms, or rather the individuals within them, even in the same narrow line of business will possess the same technological, organisational and managerial knowledge required for the production of even identical goods and services. This was well known to Marshall who put particular emphasis on the idiosyncratic nature of production knowledge in firms and it is central to the evolutionary theory of the firm and the competitive process[10].

It might be thought that the idea of knowledge as a public good with non rivalry in use and limited excludability leads directly to crisply defined production sets; that the presumption should be that all techniques are equally accessible to all firms, actual and potential. That this is not so, offers a useful lesson in the nature of technology as knowledge. The essential point is that knowledge only ever exists in the minds of individuals. What is in the public domain is information, that is to say representations of individual knowings in the form of the spoken word, demonstrations of action and codified documents and media. The possibility of economic and social order, of which a production activity is an example, depends on the relevant understandings being widely shared, as in the case of an understanding of the law and the rules of the game more generally. But much knowledge is shared in a more restricted domain, which is a chief characteristic of the division of labour with regard to productive

[10] Cf., Marshall (1920) , Nelson and Winter (1982). Marshall needed his representative firm precisely because his industries are composed of differentiated firms articulating different recipes in different ways.

knowledge. Modern societies are collectively rich in their knowledge but the specialised individuals within them are privately ignorant about other than the very restricted domain of their skill and competence. The ability to create information in a storable form and to communicate independently of face to face contact, is the basis of some of the most important technologies ever developed, in that long sequence from the invention of writing on durable materials, through printing and inks that last indefinitely, to the modern computer and information communication systems. The distinction between knowledge, and human understanding and information, is crucial to our understanding of the uneven growth and uneven incidence of human knowing. Knowledge is not in the ether ready, as it were to be "inhaled" at will without effort. On the contrary, while knowledge has the attribute of non rivalry in use, and while information may now be communicated at negligible marginal cost, this does not mean that the understanding of particular phenomena is available to anyone without effort and at negligible marginal cost. Arrow (1974) captures this very well when he considers the codes that are needed to turn information into knowledge, such that understandings can be shared and joint action in organisations made possible. But codes are an irreversible investment, they require time and effort to be accumulated, hence the importance of hierarchical education and training system that move the individual from general foundations into more specialised understanding of phenomena. Indeed, it is a commonplace to associate the more advanced forms of technological understanding with highly specialised knowledge of narrowly defined phenomena. The general purpose here is to impart understanding in common and to verify this through testing procedures but here there is a difficulty. That a group of individuals may be party to the same information flow does not imply that they will experience the same changes in their personal knowledge[11]. Knowing is unevenly distributed and, more importantly, the growth of knowledge and economic progress depends on it being unevenly distributed. We look to the idiosyncratic aspect of knowledge accumulation to identify the pioneering scientist or inventor and to identify the pioneering entrepreneur. They have much in common, they have shared the same information flow with others yet they have each conjectured that their respective worlds can be different. We do not look to the uniformity of human knowing to explain our increasing ability at problem solving but to its uneven and distributed nature. It is precisely because

[11] As any teacher knows only too well.

knowledge advances in this uneven way that we do not expect production possibilities to be sharply defined and understood in common, it is the necessary condition for progress[12].

These themes connect to the evolutionary development of knowledge as a variation cum selection process and to the parallel notion of evolutionary competition between differentiated firms who get things done differently[13]. Here it is worth remarking that the profit motive provides a powerful stimulus to the differentiation of knowledge through the search for better goods and services and better means of producing them. In general terms, a firm's profits are not made by having the same technological expectations and articulated recipes as its rivals, which, of course, means that the implementation of entrepreneurial conjectures distributes unexpected losses as well as gains throughout the system; further encouraging the revision of entrepreneurial conjectures in a never ending pattern of stimulus and response. There is a deeper issue here too. As soon as we bring the generation of new knowledge within the economic system, it is no longer possible to treat an economy as a system in equilibrium. There are always incentives to generate and apply new techniques, to advance on the competition and change the prevailing market order, and so the economic system cannot be in equilibrium unless we can conceive of human knowing being in equilibrium. Indeed, if an equilibrium of human knowing were conceivable, it would certainly usher in the stationary state indefinitely. This restless dimension of knowing, is reinforced by the public good dimensions of knowledge, in so far as non rivalry equates to increasing returns to the use of knowledge already accumulated. But it is not the use of knowledge in the production of goods and services that matters here but rather the use of knowledge in the cumulative production of further knowledge, the core of the "standing on the shoulder's of giants" metaphor. Thus production activities in firms, industries and economies are restless because under the rules of the capitalist game useful technological knowledge is restless: there are always good reasons to know differently.

[12] Thus the function of Schumpeter's entrepreneur is to act on the basis of conjectures that deviate from the status quo (Schumpeter, 1912). The consequential division of individuals into those who lead and those who follow was part of Marshall's treatment (1920) of innovation and business management too. See Metcalfe, (2007) for elaboration of this theme.

[13] There is an extensive parallel literature on the capabilities theory of the firm, one that emphasises the hard to imitate differences in managerial performance and competitive standing of rival firms in the same line of business. See Winter (1967), Nelson (1991) , Teece, Pisano and Shuen (1997) and Dosi and Marengo (2000). Montgomery (1995) and Foss and Mahnke (2000) provide valuable overviews and connections between the ideas of capabilities, routines, transaction costs, imperfect contracts and so on..

With the idea of restless technology we have begun to stray into the idea of induced invention and innovation, or the idea of economic systems as a problem generating and problem solving structures. From an economic viewpoint, the problems that command attention are shaped by the scale of the application of the solutions, and on the relative costs of different approaches to finding solutions[14] This is a complicated area in which economic historians and historians of technology have made major contributions to understanding the distinctions between different kinds of knowing (science vs., engineering, for example), the causal interdependence between them as ways of solving problems, and the status of technology as applied science (Staudenmaier, 1989, Mokyr, 2002)[15]. Nathan Rosenberg's work on this is particularly instructive, for it points to the fact that one important source of invention stimuli may not relate to anticipated changes in factor prices but rather to the internal imbalances arising within technological systems arising from the uneven pattern of inventive discovery. He expresses the point thus, "technological problems arising in industry A are eventually solved by bringing to bear technological skills and resources from industries B, C, or D". Like his imbalance principle in an individual activity, this give to the path of invention a very uneven course, a restless dynamic of development from within as solutions to problems uncover further quests for understanding. This too is a consequence of specialisation and the systemic dimensions of production activities, such that advances in one element in the production process are constrained in their application by their interrelatedness with other elements, so inducing the search for improvements in the later[16]. In this internal dynamic the solution of one problem simply serves as the creator of new problems, as if the search for improvement only serves to render unsatisfactory the prevailing aspects of the technological system[17].

Once we portray technology in terms of knowledge and activity embedded in the wider matrix of relationships in any economy then it becomes clear that we need a far finer

[14] Schmookler (1966) argued persuasively that necessity is the mother of invention to which Rosenberg (1974) responded that not all problems are solved because of the cost of doing so. This is where breakthroughs in the technology of technical change become important. Nelson (1983) has pointed out that changes in fundamental understanding often save exploration costs and redirect effort by showing were not to focus problem solving attention.

[15] Mokyr (2002) explores the theme of the origins of the industrial revolution of the 18th and 19th centuries in terms of the interdependence of the growth of prescriptive knowledge and propositional knowledge Propositional knowledge is much more than formal science and includes a catalogue of known technologies. Developments in prescriptive knowledge depend greatly on developments in propositional knowledge, but this is not causation but complementarity.

[16] On interrelatedness see Frankel, (1955).

[17] Thomas Hughes (1983) develops the imbalance principle into the idea of reverse technological salients, which give rise to critical problems, unevenly capturing the attention of engineers and inventors. .

understanding both of the benefits from specific advances and the costs of achieving them. We have reached the point where we need to pass beyond menus of inputs and outputs, and beyond blueprints and recipes to their generic purpose.

3. Technology as Transformative Activity

A useful entry point is the idea of a productive activity as humanly designed and orchestrated sets of operations that involve the transformation of materials and energy in one form into materials and energy in another form. Since the purpose of the activity is to make the final form more useful than the initial form it is natural to think of this as performing work to add value. In this perspective, technology recipes equate to transformation processes, in which the two defining characteristics are what is transformed into what, and by what means the transformations are carried out. Every productive transformation process can be written in the general form

INPUTS	$\longrightarrow$	TRANSFORMATION	$\longrightarrow$	OUTPUTS
$TIME_0$				$TIME_1$
(Materials $\oplus$ Energy)		$\rightarrow$		(Materials $\oplus$ Energy)

The symbol $\oplus$ indicates the action of 'combining with' not that of 'adding up'. The arrows indicate that every activity is a process with a time dimension, the length of an arrow indicating the time lapse between the moments of initiation (T_0) and termination (T_1) of a process (Georgescu-Roegen, 1971). That production takes time is, of course, an essential feature of real production processes. Each process of transformation is bounded, it has wholeness to it, a span of activity that must be completed before the process terminates. Time lapse and combination rate become the two operational dimensions of the process and the rate at which the process is activated can be measured either by a comparison of the differences in the state of materials at the beginning and end of the process, in broad terms, we compare what went in at T_0 with what came out at T_1. Alternatively, the rate of activation may be captured or metered, by a measure of the energy flow across the boundary of the process.

The first general point that follows from this perspective is that all production processes are joint production processes, irrespective of whether all of the outputs have an economic value. This is often most obvious in the case of chemical and physical production processes but the point is more general, for the list of outputs always includes elements of waste materials and waste energy[18]. The second general point is that we are not referring to naturally occurring processes but to humanly instigated processes, that is to say, processes that are carried out for a purpose and with a requisite degree of understanding of the transformation principles that underpin the activity. Production activities are matters of intelligent design and operation, and the guiding general purpose is to meet human needs in a superior way, or as it used to be put, overcoming the niggardliness of nature. Thirdly, most manufactured products are produced by sequences of different elementary sub-processes generating the components that are ultimately combined into the final good. As hinted at above, the point about the division of labour is that it is not simply a question of technological knowledge in the narrow sense, but of knowledge of how to organise and how to manage in terms of sequencing and controlling the systemic aspects of production within and between interlinked processes. The organising and managing may occur in many different ways, and as Coase (1937) pointed out, the boundary that segments the division of labour between different producers is an essentially economic decision reflecting a choice between management through hierarchy and management through market processes[19].

We can group the generic classes of transformation process into three broad kinds, viz:

- Physical: transformations, changing the physical form or chemical composition of materials and energy.
- Spatial: transformations, changing the location at which materials and energy are available.
- Temporal: transformations, changing the dates at which materials and energy are available.

While the three classes of transformation are logically distinct, in a modern economy they are complementary and jointly underpin its input: output structure within and between production

[18] On the thermodynamic principles behind transformation processes and the distinction between energy and exergy see Buenstorf (2004)

[19] For a valuable discussion of the relation between organisation and production see Langlois and Foss (1999)

establishments.. Some examples will help. Under the first category we could consider the fashioning of the body of a motor vehicle from a sheet of steel, or the production of a synthetic drug from various chemicals, or the production of computer records of financial transactions. In each case the application of energy induces a change in physical state of the material substrate of the process. All activity that we classify in terms of manufacturing falls into this first category, it involves some changes in form of or composition of materials through processes of separation or synthesis, or assembly. Agriculture falls within this category too. Though, in agriculture, the processes are biological and chemical: the direct energy input comes primarily from the sun, and the material inputs are either carried over from the previous "seed" harvest or are added as human-made supplements to the fertility of the soil. In the second category are found all the transport activities that move people, materials, goods, information and energy, to different places to satisfy the spatial dimension of distributed ways of living and producing. We include here not only the transport of electric power and material goods but also the electronic transmission of information on the internet or by other media. In the third category are found the general class of storage activities that preserve the continued existence of materials or energy over time. A battery is a device for the inter-temporal transformation of energy, a refrigerator a device for the inter-temporal transformation of perishable food, and a book or a computer memory are devices for the inter-temporal transformation of information[20].

Much is made of the fact that modern economies are service economies with some 70% or more of GDP accounted for by a heterogeneous collection of what previous writers called tertiary activities to distinguish them from agriculture, extraction and manufacturing (Clark, 1944). Where do services fit in this scheme? The answer is very precisely within the three categories of transformation. What we refer to as transport, whether of goods or people, is a typical example of a service activity, as are many storage activities such as those carried out by retailers when making goods available for view by customers. In the case of personal services, the transformations are carried out on the individuals acquiring the service; the person is the material basis for production. Thus the quintessential hairdresser carries out a physical transformation of the client, while the surgeon does the same when a medical intervention is performed, as does the transport operator when performing a spatial transformation of the passengers.. Many of these service activities are in reality maintenance

[20] There are many different possible taxonomies of production activity, dividing and further subdividing our three broad categories. See Buernstorf (2004) for an excellent discussion.

procedures on humans and might, from this perspective, be classed along side the repair and maintenance of countless physical devices. Information services and related activities also fit naturally within the general transformation scheme, in that they involve the manufacture, capture, transport and storage of information in different kinds of media. Although, computers have replaced the ledger and manuscript as stores and manipulators of information, the underlying principle is the same, though the clerical function is no longer performed with pen and paper, nor is the output of this recording process communicated by a postal service. In the case of financial services, a modern bank is, among other aspects, a recording system for capturing and transforming, communicating and storing records of the levels and changes in the wealth of its clients. In fact the manufacture, transport and storage of information has always been essential to a monetary market economy but it has taken the IT revolution and the electronic manipulation of materials to make this basic feature manifest.

This said, what is the connection with economic perspectives on technology outlined in the previous section, for the two are very different? Production is carried out for intelligent purposes; it is purposeful in the technological sense of particular combinations of causes leading to particular effects, and also in the economic sense of generating a value to the outputs that is intentionally greater than the value of the material inputs. Although value-added is a correlate with the intelligent work that is carried out in the production process, it is not grounded solely in the physical, organisational and managerial aspects of production but in the wider determination of revenues and costs that are associated with consumption and the supply of factor services Doing work implies also implies something that is worked on, and something that does the work and this is the basis for the distinction between produced means of production and factor inputs. It is the later that do the work, and value-added equates to the incomes that are generated. Since transformation involves action on materials through the intelligent deployment of energy it follows that the factor services contributed by the primary inputs must be closely connected with the purposeful, controlled application of energy to those materials. Here the further distinction is made between the primary productive factors and the flows of productive services that are drawn from them. The factors or funds, as Georgescu-Roegen (1971) calls them, perform the work in the sense that they are the vectors to apply and control the flow of energy. To focus on the later, the economist often suppresses the role of the myriad forms of materials that contribute to the scheme of production. As Carter puts it "the coal and ore and steel and chemicals, and fibres and aluminium foil; sausage casings, wire products, wood pulp, electronic components, trucking and business services, remain enclosed in the economic black box that converts primary inputs into final output" (p. 4). One can certainly do this, resolving the production of materials and inanimate energy at successive stages of production into the work done by the factor inputs alone, until the initial extractive stages are reached. In this way one distinguishes the direct from the indirect quantities of the primary inputs involved but at a cost. First one loses sight of the systemic interdependence of the production process, an elaborate division of labour not only within particular processes but between them. Secondly, as we shall comment on below, the economic analysis of technical change is severely distorted if it is reduced to the saving of factor inputs alone, whether directly or indirectly.

Among the primary factors primacy of attention must be devoted to human effort and the many forms of productive service that it produces, each kind premised on a particular specialised body of understanding. The knowledge of a transformation process and the purposes for which it is directed exist only in human minds; activities have to be invented, designed and constructed as well as operated. The traditional role of labour as a primary factor is to supply energy to operate tools in an intelligent, fashion, or to control the application of inanimate energy via the use of machinery and other capital structures. Since different stages of production are usually involved, organisational, supervisory and directing inputs are also required to gather and communicate the information necessary to keep the bundle of processes operating in a balanced way within the unit of production. These non physical inputs also involve the expenditure of energy and absorb material inputs, and the knowledge of how to organise, supervise and direct is on a level of importance with the knowledge of the physical processes involved. An element of joint production is involved here too, in that the output of the process are the mentally and physically tired workers, whose lost energy must be replaced in other, "household", production processes if the activity is to continue. What is far less readily recognised is that more knowledgeable workers may also be an output of the production process: Adam Smith certainly understood this but the point is more general, in that a production plant is a site of learning as well as transformation in the narrow sense, an idea that has become commonplace in the notions of learning by doing and learning using[21].

[21] See Rosenberg,(1982), chapter6.

The case of "land" as a primary agent, the original but not indestructible powers of the soil, is rather straightforward, it performs its services by serving as a spatial net to capture solar energy and by its contribution to the growth of plant material through the release of mineral sources of chemical energy. When we turn to the idea of capital as a factor of production the issues are rather more complicated.

In so far as we focus on capital goods and structures, these are produced, durable and semi durable outputs of the production system. To this degree they are like land (and the sea), and like land and labour they are partially worn out during any production process and need to be maintained or replaced. Capital goods and other capital structures are equivalent to other produced material and energy inputs, except for their longevity, but this difference in the rates of durability captures only part of the nature of capital goods and structures. Their more fundamental dimension is that they are designed and constructed to facilitate the application of useful energy to the materials in the production process, including in this the production of energy in different forms. We speak of tools that are activated by human energy and of machines that are activated by inanimate energy. The sustained growth of machine-based production methods is the correlate of the growing application of inanimate energy through ever more sophisticated means to produce different forms of energy, to transform one energy form into a more useful one, and to control the work that is done in countless different ways. As Paulinyi (1986) has pointed out, the crucial historical step that makes this abridgement of labour possible is the mechanisation of the relation between tool and material. In turn, this required the surmounting of a wide range of technical problems in relation to the control and measurement of motion, before human or animal energy could be replaced by inanimate energy. Thus, it is not surprising that capital goods are the focus of so much inventive activity in order to solve interrelated problems of energy and material transformation, or that their use has provided such a stimulus to the advance of the natural sciences (Rosenberg, 1963). The thrust of the history of technology is that capital goods and capital structures of an ever-expanding range have been the principal vectors through which the knowledge-growth connection is made. Knowledge of new transformation processes, almost invariably, has been embodied in sets of new capital instruments. Not only do we find in the record an infinite variety of new machines to capitalise on new materials and to produce entirely new kinds of commodity but we also find new machines to make the machines.

The idea that capitalism is a system characterised by the production and use of capital goods, or produced means of production more generally, would seem to be so obvious that it is scarcely worthy of further comment. Yet, historically, the concept of capital goods (and especially its close relations, 'capital value' and the 'time phasing' of production activities) have been associated with a long series of controversies that embody and reveal deep fault lines between different formulations of the economic process (Kurz and Salvadori, 1995). When economists assert that "capital" is a primary factor they are not only referring to these machine complexes or to goods tied up in general but rather to a quite different point that production takes time[22]. This lapse of time locks up resources that could otherwise be used in consumption, as with the classical idea that the wages of the workers form a capital value fund, just as do the materials on which they work. This idea is extended by later writers (Jevons, for example, 1879) to include the capital goods in which the fund is temporally embodied. Whether capital value is a productive agent on a par with human agency and land, is a deeply contested point[23]. The sense in which it can be thought of as a given quantity to constrain production activity is not at all clear, once we depart from Marshall's short period. Outside of this context, the long period quantities of the various capital goods and structures and the prices at which they are produced and valued are the outcome of investment decisions and thus endogenous to the system.

Among the different approaches to capital as productive agent, the Austrian school has made important contributions. Ludwig Lachmann, for example, in his book, Capital and its Structure (1956), begins from the classical position that capital has no single unambiguous meaning and what it is crucial to comprehend is the *heterogeneity* of forms of capital goods and the multiple specific uses to which many capital goods can be put. Moreover, capital goods are rarely used in isolation and it is the complementary combination of different capital goods within specific production plans that gives capital its structure. The theory of capital is about patterns of combination and use, the morphology of forms (p. 4) in which the

[22] As Jevons (1879) expressed it, "It is a matter of time elapsing between the beginning and the end of industry" (p. 248). J.B. Clark (1899) developed the Jevonian perspective into the doctrine that the capital of a society is a single organic whole, not any particular instrument of production. It is permanent fund measured in value units, though at any moment it is largely (not entirely) embodied in things of a sort which more or less regularly wear out, are used up or become obsolete, and are replaced by other items of the same or different prescription (p. 460) That it may be viewed as a value fund is one thing, its permanence is quite another. The idea that time elapsing has a cost which constrains investment activity, is reflected in Marshall's concept of waiting, and in Fisher's notion of time preference or impatience.

[23] For contrasting views, the standard references are Harcourt (1972), Bliss (1975) and Kurz and Salvadori (1995)

composition of a functionally differentiated stock is as significant as its magnitude. From an economic viewpoint capital goods find their meaning in production plans and it is in the context of such plans that they acquire a forward looking value. These values are always transient, since, in a progressive economy, the capital structure is always being reformed, particularly in response to changes in knowledge. Maladjustments occur and capital value is often lost in the process and the role of the entrepreneur is to reallocate existing capital goods to new production plans and attempt to turn loss into profit. The idea of capital structure as an emergent feature of the market economy, parallel to productive knowledge as an emergent feature, is an appealing way to interpret Lachmann's argument in modern terms. .There is no need at any point for such a system to be in equilibrium, the prevailing set of capital goods may always be misallocated relative to perceived opportunities to utilize their services. The same physical set of capital goods may have over their economic lifetime a plethora of occupations and values none of which need bear any relation to the cost of their production. There is nothing mystical, or particularly significant about capital value, it is what the market says it is.[24]

4. The Pattern of Advancing Technical Knowledge

The real benefit of focusing on the material and energy based nature of transformation schemes is that they bring into relief the three great strands of technological advance in the history of technical invention since the earliest times[25]. These are the discovery of new sources of inanimate energy and the means to harness energy to different production tasks, the discovery of new materials contained in the earth's crust, atmosphere and oceans, and the

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[24] One of the few economists to consider the idea of a structure of capital instruments in any formal way is Salter (1960) in his account of the mechanisms through which productivity growth is influenced by the spread of new techniques embodied in particular plants. Salter took the relation between what is meant by technology and the production function a good deal further. The link between knowledge and the production function is complex and reflects knowledge of differing degrees of generality and proximity to the process of production, from basic principles of fundamental phenomena to the further knowledge required to apply them to production and knowledge required for day to day operation. Thus some knowledge is relevant to the design of production facilities and some to their operation, including the operation of the plants that build the facilities in question. Frankel (1955) also examined the interrelatedness of capital and the technical interdependence of the components of an assemblage of capital goods within a plant, focusing on the adoption of innovations and the potential disadvantages of already acquired sunk investments. Apart from the work of Salter and Frankel there appears to be relatively little formal economic treatment of the structure of capital good complexes in an economy and next to no discussion of the implications of assemblages of capital goods for the progress of invention and innovation, the themes that Smith and Babbage had identified in the early stages of the industrial revolution.

[25] The parallel invention of organisational and managerial technologies (social technologies as Nelson (2005) expresses them) is a quite different but far more difficult to document story, partly because these dimensions of knowing have no built structure as counterpart.

discovery of synthesised materials that have no natural existence but are combinations of the materials in the earth's endowment. Within each strand there are multiple sequences of technological development and any one sequence may apply differentially to the three kinds of transformation with important interdependencies. The outcome is the greater productivity of activities in the economist's sense but this masks the fact that productivity growth is not only a matter of efficiency enhancement in producing a given list of goods but the result of greatly extending that list. Product innovation matters at least as much as process innovation and the major histories of technology reflect these distinctions in great detail, tracing the development of technologies to harness the inanimate energy of wind and water, namely, the sailing ship, the windmill and the water wheel is followed by the development of steam power and electricity and so on to the computer and its complementary consequences[26]. The search for ways to harness these new energy sources provided a continual stimulus for the invention of machines and the corresponding development of branches of engineering and supporting fundamental sciences that result in the abridgement of human effort, whether physical or mental. The development of the natural sciences certainly plays an important part in this story of co evolution of activity and knowledge, but the stimuli undoubtedly run both ways as the development of working, practical knowledge stepped ahead of formal understanding and stimulated a search for general principles[27].(Mokyr, 2002). As a consequence, economic development and growth is never, a case of steady, balanced proportional expansion but rather it is a matter of uneven development, as entire new branches of production are created, develop and diffuse, reach maturity and then slip into decline. This qualitative as well as quantitative unevenness in the development of the productive fabric is matched closely by the uneven development of useful knowledge[28].

Of all the economists who have written on the interplay between new energy sources, new materials and new capital structures, Marx's account is pre-eminent[29]. As is well documented, he describes the evolution of capitalism across different regimes for organising processes of transformation, from manufacture to modern industry. Manufacture required the bringing together within one location various independent crafts, while subdividing these

[26] A by no means exhaustive includes Gille, 1986; Singer, Holmyard and Hall, 1958; Klemm, 1959; Usher, 1929, 1954; Landes, 1969, Mokyr, 2002, Hughes, 2004,
[27] For a fascinating account of mechanical invention and the development of power technology in medieval times see White, (1962).
[28] This is a central theme in modern evolutionary growth theory (Nelson and Winter, 1982, Nelson, 2005) and in the earlier writing of Simon Kuznets (1954, 1971, 1977)
[29] See in particular, Rosenberg (1982), chapter 2.

tasks into a fractional division of labour in which the proportions of each step are set by their respective rates of throughput. Modern industry, by contrast, is marked by the invention and use of *machinery*. The tools and instruments are connected to a power source, which is increasingly based on inanimate energy, culminating in what Mumford (1934) was to term carboniferous capitalism. From this follows a detailed ‘division of machinery’ with groups of capital goods forming production complexes subject to the fractional principle of multiples. In parallel there is a second major step in this development process. This is the emergence of the industries to produce the machine and capital structure, with more and more branches and a more refined division of specialisation, so forming the technical foundation of modern industry in the capacity to produce machines capable of many varied tasks with materials as refractory as iron. In turn, this requires and stimulates the creation of the system of river steamers, railways, ocean steamers and telegraphs, which in turn required the “cyclopean machines to fashion them from iron” (p. 363). Thus the machine was taken in hand, and machines constructed by machines. What mattered in Marx’s account was the extension of the machine-manufacture methods to the making of machines, so eliminating a fundamental constraint on the rate at which they could be created and thus a major constraint on the expansion of a system premised on the production and application of inanimate energy. As produced means of production, their supply not only became infinitely elastic, the conditions of supply became the focus of multiple inventive efforts and the focus of a technological revolution (Paulinyi, 1986).

Among other leading students of technological change, Usher captures extremely well this interplay between the discovery of new energy sources, new materials and the creation of new kinds of transformation process. One reason why Usher’s history of these events is so compelling is because of his attempt to develop a non-equilibrium theory of invention, to pose and answer the question, ‘How do new things happen?’(p. 60). The approach is notable for two reasons: it is combinatorial, and it is systemic, the development of technology is the interplay between parts and wholes and some parts contribute to many wholes. For Usher, invention is a contingent social process applied to devices that are complex systems, and inventive success by any individual is not preordained but depends upon the context, which includes the stages already reached by other individuals. Strategic inventions are defined by the combination of multiple acts of novelty, the higher degrees of synthesis required to achieve their successful combination, and the important role of acts of insight that identify problems and inconsistencies in design, and thus stimulate critical revision. Moreover it is through the combinatorial nature of the process that it remains open ended; Usher's temporal sequences do not have an end in any present moment (p.46). .

5. Summary

We have covered a great deal of ground, although much has been left unsaid, the price one normally pays for trying to provide a short discussion of technology in economic analysis. One might sum up as follows. Technology as the way of getting things done is more than a matter of lists of inputs and outputs; it is more than a matter of blueprints and recipes for it depends greatly on the human dimensions of skill and knowing. It is inseparable form the idea of a division of labour and a correlated division of knowing, ultimately concerned with the productive transformation of material and energy to meet human needs. Thus it is capable of many forms of expression and it is the uneven nature of knowing that gives to an economy its evolutionary foundations and its dynamic properties. This is the heritage of Smith, Marx, Schumpeter and Marshall; it is capable of a great deal more development.

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